What is Climate-Smart Forestry?

A definition from a multinational collaborative process focused on mountain regions of Europe

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Abstract

Climate-Smart Forestry (CSF) is an emerging branch of sustainable forest management that aims to manage forests in response to climate change. Specific CSF strategies are viewed as a way forward for developing suitable management responses and enhancing the provision of ecosystem services. However, there is currently a lack of comprehensive and cohesive assessment to implement CSF. This paper describes the step-by-step process that developed a comprehensive and shared definition of CSF, and the process for selecting indicators that assess the “climate-smartness” of forest management. Adaptation, mitigation and social dimensions are the core focus of the CSF definition, which recognises the need to integrate and avoid development of these aspects in isolation. An iterative participatory process was used with a range of experts in forest-related fields from the CLIMO project, this was subsequently supported by a network analysis to identify sustainable forest management indicators important to CSF. The definition developed here, is an important first step in to promote CSF that will aid practice in the forestry sector. It can be used as a template across Europe, tailored to local contexts. Further work communicating CSF to practitioners and policy-makers will create a CSF practice and culture that will help to safeguard future forest economies and communities.

Keywords: sustainable forest management, adaptation, mitigation, social dimension, bioeconomy, indicator

1. Introduction

In recent years the term Climate-Smart Forestry (CSF) has become increasingly common in forestry circles permeating into academic and sector-specific culture (Hansen et al., 2010; Jantke et al., 2016; Nabuurs et al., 2018; Yousefpour et al., 2018). The CSF concept is emerging as an important next step in furthering the goals of Sustainable Forest Management (SFM) and the sector's response to the threat of climate change. The Intergovernmental Panel on Climate Change (IPCC) places great emphasis on forests and associated activities, as crucial for mitigating the impacts of climate change (IPCC, 2014). In order to meet the Paris Agreement goals, considerable contributions will be required from forests, as nations are simultaneously aiming to reduce forest degradation and enhance carbon sinks (Rockström et al., 2017). As a consequence, forests can be viewed as both an issue and a solution, with healthy and widely beneficial forests the ultimate goal.

Forestry has been placed at the forefront of action to mitigate climate change through afforestation and carbon sequestration efforts (Bastin et al., 2019). Subsequent management strategies will be significant, as these will determine and regulate emissions, as well as producing ecosystem services that will support and enhance dependent communities. The visibility of action through afforestation provides clear metrics and mitigation goals that currently align with the aims of many governments that are pledging to massive planting commitments without future planning for these new forests. Planting alone does not guarantee mitigation; careful establishment and subsequent management is required to support the forests, communities and economies. CSF definition and indicators could be vitality important for guiding climate-smart decision-making. Moreover, they could be components of a broader landscape-scale strategy, which continuously develops with complex socio-ecological systems to achieve sustainable development goals (Denton et al., 2014). Coordination and collaboration between stakeholders to create a shared vision is paramount to achieving such goals (Folke et al., 2010; Kok et al., 2014). Often institutional and technical capacities need to develop with working concepts such as CSF to help assess and promote effective application by stakeholders.

1.1. Climate-Smart Forestry definition

The climate-smart concept originated with agriculture (FAO, 2010a) and recognises the need for "*an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate*." This approach, which is adopted by Nabuurs et al. (2018) with regard to forestry, describes three main objectives using climate-smart agriculture as a template: (i) sustainably increasing production and incomes; (ii) adapting and building resilience; and (iii) reducing or removing GHG emissions (FAO, 2010a; Zilberman et al., 2018). Nabuurs and colleagues (2018) focus on the third objective of reducing or removing GHG emissions through forestry.

A Web of Science database query with the keywords 'Climate-Smart Forest' resulted in 106 publications since 2000 (Figure S1) with only four articles explicitly addressing the subject of 'Climate-Smart Forestry' in Europe as the main focus of the articles (Jandl et al., 2018; Nabuurs et al., 2018, 2017; Yousefpour et al., 2018). CSF literature over the last eighteen years addressed a number of issues including GHG emissions (Yousefpour et al., 2018) carbon sequestration with a strong cluster of publications on REDD+ (Nabuurs et al., 2018; Vass and Elofsson, 2016), land use and habitat change (Pussinen et al., 2009; Smiraglia et al., 2016) impact on tree species diversity/distribution and forest structure (Del Río et al., 2016), wildfire regimes (Fernandes, 2013; Sousa-Silva et al., 2018) and the resulting effects on management and decision-making (Hansen et al., 2010). Beyond the CSF concept, there is an emerging area focusing on mobile applications that collect forest data through citizen science and professional monitoring networks (Yang et al., 2015). A thorough analysis of the CSF related literature is provided in Appendix A of supplementary material.

No widely adopted definition currently exists for CSF, therefore, the term is being interpreted in a number of ways, which mostly focus on the reduction of greenhouse gas (GHG) emissions and effective carbon sequestration, as the core mitigation actions (Nabuurs et al., 2018; Yousefpour et al., 2018). Socio-ecological systems have mostly not been addressed so far in CSF with the majority of studies based on modelling techniques mainly addressing carbon sequestration, substitution and climate impacts (Nabuurs et al., 2018; Yousefpour et al., 2018). For this reason, practical guidance for assessing and implementing

CSF is needed to support forest regions and to promote climate-smart management within the context of diverse social-ecological systems that they support (Folke et al., 2016; Melnykovych et al., 2018).

1.2. From SFM indicators to CSF indicators

Forests provide valuable ecosystem services that contribute to social capital, support rural economies and generate significant income for communities (Biber et al., 2015; Melnykovych et al., 2018). Folke et al. (2016) highlighted that social and ecological interests are inextricably intertwined, shaping one another along spatial and temporal trajectories, which feedback to influence opinion and behaviour. These changes to external effects, such as climate change, require shedding legacy social-ecological systems to be replaced by new social-ecological systems capable of responding to current and emerging challenges that threaten human well-being. Social-ecological legacy and adaptability present as much an uncertainty and unpredictability, as climate change impacts, therefore forest managers rely on structures, expertise and guidance in which to operate to minimise unwanted outcomes. SFM Criteria and Indicators (C&I), payment for ecosystem services (PES) and certification schemes represent such tools and expert guidance. In particular, C&I are a widely-applied policy tool for monitoring, assessing and reporting on SFM and for supporting the definition of forest management priorities and targets (Santopuoli et al., 2016; Wijewardana, 2008; Wolfslehner and Baycheva-Merger, 2016).

C&I for SFM may be required in areas where the capacity to collect, measure, record and assess data is challenging. Here guidance can increase the visibility and highlight the importance of the services that forests provide to the wider landscape. In a similar way, a definition and indicators for CSF, can enable forestry professionals to respond to current uncertainties in forest management. Processes such as SFM recognise that our understanding of forest ecosystems, socio-economic conditions, technologies and stakeholder priorities will continually change. Therefore, indicators must be flexible enough to adapt to emerging challenges and demands (Linser et al., 2018), but also highlight when new guidance is needed and management should be reassessed.

This paper presents, for the first time, a broad definition of CSF, which can be subjected to further testing and verification. The definition was developed through an iterative deliberative process that involved confrontation among a multidisciplinary group of experts from 28 countries (http://climo.unimol.it/) participating in the COST action CA 15226, Climate-Smart Forestry in Mountain Regions (CLIMO). Developed for policy-makers and practitioners, the CSF definition initially aimed to guide European forestry, but can also be used as a template in other areas of the world. Moreover, the paper describes the process used to select indicators, enabling assessment of the climate-smartness of forests in support of SFM and limiting the negative impacts induced by climate change. Section 2 describes the definition building process as well as the methodology for the network analysis of the SFM indicators. The results of the network analysis and the CSF definition are described in the section 3.1 and 3.2 respectively. Section 4 discusses the implications for European forestry and climate policy, while outlining further work and next steps. Section 5 covers conclusions.

2. Material and methods

2.1. The definition process

The CSF definition process involved participants of the EU COST Action CLIMO during and between three separate meetings (Table S1). Deliberative processes are used in diverse environments from shaping of international policy to decision-making at a community level with the aim to build common consensus on a wide range of perspectives, leading to collective agreements and actions (Dietz, 2013; Wolf and Klein, 2007). Development of the CSF definition for CSF and relevant indicators for monitoring and assessment (Figure 1), aims to build a guiding framework for future research, practice and policy.

The multidisciplinary background of CLIMO forest professionals fostered an iterative and discursive participatory approach that has proven effective for forest governance and wider decision-making processes. This enabled participants to share views on forest management and CSF, identifying important linkages between SFM and forest ecosystem services that would prove beneficial for CSF.

Säynäjoki (2014) suggests that confrontation of perspectives is a key stage for groups that aim to elicit and examine individual reasoning, allowing for broader reflection on complex issues. Therefore, the definition was tested and challenged over the series of meetings (Table S1) until a consensus was reached with the current version. These meetings were part of a longer process planned to take the definition from an initial concept inspired by Climate-Smart Agriculture and the Forest Europe C&I for SFM, through this initial definition. Further amendments are envisioned after consultation with policymakers and practitioners with the ultimate aim of developing a CSF toolkit for forest managers.

[Insert Figure 1 here]

At the inaugural meeting (Trento, Italy, February 2017), Working Group (WG1) was formed to develop a comprehensive definition for CSF and to identify criteria for CSF assessment and monitoring to generate baselines for future research, practice and policy. Working Group 1 was the largest of four working groups with a diverse range of participants with backgrounds ranging from forest management to ecophysiology and ecology, from soil science to forest policy, as well as genetics and landscape management (Table S2 - Appendix B, in Supplementary material). In the first meeting, the general aim and methodology for reaching a definition and selecting criteria were discussed. A sub-group of WG1, with members from the COST Action CORE group and participants from other working groups, was established with the specific task of developing a CSF definition. This sub-group met in Sofia (Bulgaria) in September 2017 to produce a preliminary (incomplete) draft of a one-page definition. This was shared by email for consultation and amendment first with the sub-group participants who had not been able to attend, and second with all members of the COST Action between October 2017 and February 2018. In February 2018, the sub-group reconvened at the annual CLIMO meeting in Sofia to come up with a first full draft that could be presented during the plenary session to all participants.

At the end of the third meeting, the definition was challenged, in an open discussion, by representatives from each WG by providing comments, suggestions and amendments that had been compiled and synthesised from each separate WG. These were presented to WG1 and discussed until a consensus/agreement was reached to either integrate, modify or reject the proposed changes. This confrontational method allowed all suggestions to be put forward for debate, defence and negotiation, which is an increasingly necessary stage for contentious issues and areas of uncertainty (Mavrommati et al., 2017; Pellow, 1999; Runhaar et al., 2016). This important step ensured that expectations, inherent bias and agendas were challenged, so that the definition can be judged to be developed through a comprehensive, transparent, legitimate and effective process.

A high number of CLIMO members actively participated in the development of the definition. Overall, 48 members contributed from 19 countries with a range of expertise and management experience (Table S2 - Appendix B, in Supplementary material).

2.2. Determining criteria and indicators

Since the 1990s, many international processes developed principles, C&I to support SFM worldwide (Castañeda, 2000). In Europe, the pan-European set of C&I for SFM is considered one of the most important tools for assessing, monitoring and reporting on SFM, and is implemented widely among European countries (Santopuoli et al., 2016; Wolfslehner and Baycheva-Merger, 2016).

Indicators for assessing CSF include adaptation and mitigation strategies, and also consider the multiple benefits that forests provide to society. The CLIMO partners agreed to identify CSF indicators, from the pan-European set (Table 1), that address adaptation and mitigation, but at the same time observe a number of forest ecosystem services, which are important for supporting smart decision-making in forestry. For this reason, the Common International Classification of Ecosystem Services (hereafter CICES) version 4 (Haines-Young and Potschin, 2012) was used to select the most relevant forest-related ecosystem services (Table 2). Maintaining ecosystem services is crucial for supporting human well-being, however the quality of these services relies on healthy forest environments and sustainable forest management. For this reason, all ecosystem services were considered equally important in this study.

[Insert Table 1 here]

During the meeting in Sofia 2017 participants were asked to (i) define whether or not the SFM indicators supported monitoring of adaptation and/or mitigation forest management strategies; and (ii) identify the forests ecosystem services that can be monitored by indicators previously identified. Beyond the SFM indicators, four additional forestry indicators (i.e., management system, slenderness coefficient, vertical and horizontal distribution of tree crowns) were included in the process by CLIMO participants, due to their accessibility through National Forest Inventory data and field surveys. Participant choices were organized in a matrix, within which forest ecosystem services were columns, and SFM indicators were rows. Three matrices were created, one for adaptation, one for mitigation, and one for adaptation and mitigation combined, namely CSF (see Figure S2, S3, and S4 appendix C).

[Insert Table 2 here]

The Analytic Network Analysis was implemented to identify the most relevant indicators for assessing CSF. In particular, a Two-mode network analysis was performed in UCINET software to manage the two sets of separate entities (Hanneman and Riddle, 2005), specifically SFM indicators and forest ecosystem services. This approach is similar to that undertaken by others using C&I for selecting indicators of SFM through a participatory approach (Mendoza and Prabhu, 2000; Santopuoli et al., 2012), and support decision making in SFM (Wolfslehner et al., 2005; Wolfslehner and Vacik, 2011). Centrality measures, such as degree, k-core, betweenness and closeness were calculated to weight and classify indicators into groups of CSF relevance. Additionally, key arguments from CLIMO participants in response to the group's discussion and debate of indicators, iteratively contributed to shape the CSF definition.

Results were displayed as a network through a fuzzy cognitive map carried out with NetDraw software (Borgatti et al., 2002). Indicators and forest ecosystem services are the nodes of the network, while the ties reflect the suitability of indicators to monitor adaptation, mitigation or both, as well as the forest ecosystem services they address. In the two-mode network, the ties are unidirectional flowing, from the indicators to ecosystem services, therefore no connections between nodes of the same entity (i.e., among indicators) exist. Further details about network analysis and structure can be found in the Annex C in Supplementary material.

3. Results

3.1. Network analysis

Twenty-three forest-related ecosystem services were selected and used in the CSF assessment (Table 2). Twelve out of 23 belong to the regulating section, six to the provisioning and five to the cultural section. However, regulating (i.e., sequestration, biological control, and refugia) and provisional services (i.e., raw materials and PBP) were highly connected with most of the indicators (Figure 2 and Figure S3). By contrast, cultural ecosystem services, such as spiritual, recreation, tourism and aesthetic, were slightly less connected.

Results show that a total of 29 indicators were selected by participants as suitable to assess adaptation and mitigation, then were subsequently used to perform the network analysis. Twenty-five of these indicators came from the original 34 for SFM, plus the four new indicators identified by the participants (Table 2). Seven indicators of criterion 6 – socio-economic function (i.e., 6.1 forest holdings, 6.2 contribution of forest sector to GDP, 6.3 net revenue, 6.4 expenditure for services, 6.5 forest sector force, 6.6 occupational safety and health, and 6.11 cultural and spiritual values) and two indicators of criterion 3 -forest productivity (i.e., 3.3 non-wood goods, and 3.4 services) were not selected. This highlights that many socio-economic aspects were lost when considering adaptation and mitigation as central pillars of CSF (for the group of experts consulted).

The centrality variables (Table 3) confirms this trend showing that indicators 6.8 trade in wood and 6.1 accessibility, are two of the most peripheral indicators. Nevertheless, nine out of 29 indicators are central to the network, showing a degree of 23, which means that they have connections with all the 23 forest ecosystem services considered in this study.

Moreover, contrary to the expectations, indicators 1.4 carbon stock, 1.2 growing stock and 4.5 deadwood, are positioned peripherally in the network due to their linkages with regulating services and poor connection with other forest ecosystem services. Conversely, the new indicators provided by CLIMO participants obtained higher and medium centrality values.

[insert Table 3 here]

Four groups have been identified based on the centrality values (Table 3) and the position of nodes in the network (Figure 2).

1st core group indicators

This group includes 12 indicators with higher centrality values (Table 3), positioned centrally in the network. Strong linkages are demonstrated to indicators in assessing the preservation of forest resources, such as indicators 1.1 forest area and 4.7 forest fragmentation. Most of the indicators of criterion 4 – biodiversity conservation - are included in this group, such as 4.3 naturalness, 4.1 tree species composition and 4.9 protected forests. Moreover, the group includes indicators which address planning and promoting sustainable timber production, such as 3.5 management forest plan, 6.9 energy from wood and 6.7 wood consumption. Monitoring these core indicators will be necessary in order to promote CSF through the adaptation and mitigation by forestry practices.

[insert figure 2 here]

2nd core group indicators:

This group centres upon indicators of criterion 2 – forest health and vitality, including 2.2 soil condition and 2.3 defoliation, as well as indicators of criterion 4 – forest biodiversity including 4.2 regeneration, 4.6 genetic resources, and 4.8 threatened tree species. Indicator 5.1 protective forests can be considered an overarching indicator for this group. Results show that these indicators have higher centrality values and similar capacity to monitor both provisioning and regulating services. Interestingly, this group has also some connections to cultural ecosystem services suggesting that management under CSF would directly enhance cultural services of the forest ecosystem. For these reasons they are considered core group even though they occupy a peripheral position in the network.

1st peripheral indicators:

This group includes indicators that demonstrate the influence of silvicultural interventions at stand level which effect tree competition, tree growth and forest production (3.1 increment and felling, 1.3 age structure, 1.2 growing stock, 1.4 carbon stock and 4.5 deadwood). These indicators are mostly linked with regulating ecosystem services. The lower centrality values, especially for indicator 3.2 roundwood and 6.8 trade in wood, and the marginal position in the network identifies them as peripheral indicators. Nevertheless, they provide important information to direct forest management toward more efficient mitigation actions, particularly related to the improvement of carbon stock and slowing down the natural release of carbon into the atmosphere.

2nd peripheral indicators:

This group is composed of a single indicator, 6.10 accessibility for recreation, mainly due to the marginal position rather than the relatively low centrality values. However, the marginal position on one hand and the power of connection with cultural ecosystem services on the other identifies accessibility as peripheral indicator. This does not diminish its important role for assessing CSF, particularly in mountain forests for which forest roads are crucial not only for recreation purposes but also to ensure harvesting activities (i.e., sanitary interventions), counteract forest fires and reduce forest management costs.

Results highlighted perspectives of CLIMO participants with regard to monitoring and promoting CSF. During the analysis the main themes which emerged from the participatory process and network analysis (Figure 3), are summarised below:

- *CSF is not limited to regulating ecosystem services.*
- *Strengthening of adaptation and mitigation measures to support forest management strategies.*
- *Forest health and vitality are crucial for protection and maintaining other forest functions.*
- *Maintaining forest biodiversity is key to counteracting climate change.*
- *CSF has to maintain and enhance the provision of wider forest ecosystem services.*

- *Integration of social dimensions is key for implementing climate-smart forest management.*

[insert Figure 3 here]

3.2. Climate-smart forestry definition

The working group participants developed a CSF definition that included five sections: a brief overarching CSF definition, sections on adaptation, mitigation and social dimensions and a concise summary statement about CSF (Box 1).

[insert Box 1 here]

4. Discussion

4.1. CSF definition and indicators

CSF continues to develop, as a concept and in practice, but enhancing and facilitating clear implementation pathways could be the difference between forest communities either thriving or declining. The underpinnings of CSF are already integrated into literature, policy and practice through established and accepted frameworks (i.e., adaptive management, mitigation and ecosystem services) under the SFM umbrella, which provides a platform to develop targeted and relevant climate-smart expertise. Climate change is challenging current management systems with wide reaching impacts for forests and societies; these challenges are heightened when considering vulnerable areas such as mountainous regions. Therefore, rapid action that fosters greater understanding of climate induced changes will require meaningful cooperation between practitioners and policy-makers. Communication of relevant advances in the field is needed to address these issues with targeted knowledge and management approaches that can be applied and adapted to local areas. In order to continually refine the assessment of CSF indicators and to promote communication among policy-makers, forest researchers and practitioners, a CSF approach that develops understanding and impact needs to be established.

In section 3.1, indicators considered central to adaptation and mitigation for forests (carbon stock and growing stock: see Figure 2) were identified as peripheral for CSF, whereas core group indicators were more explicitly related to human activities, management actions and interventions (fragmentation, wood consumption, wood energy and management plans etc.). These focus on the combined processes and interactions between forests and human intervention through forestry activities. However, indicators such as trade in wood, roundwood, as well as increment and felling fall within the 1st peripheral group despite their association with management. Linser et al. (2018) stress that the discussion around SFM will continually evolve and respond to socio-economic aspects and emerging challenges. Therefore, subsets of indicators might be necessary to link with other sectors or tailored to fit particular issues such as climate change. CSF indicators may change with the input from more diverse range of stakeholders or more focussed geographical ranges. This paper differs from those of Nabuurs (2018; 2017) and Yousefpour (2018) as it includes adaptation and mitigation as broad frameworks, and emphasises the importance of the social dimensions of forestry. Additionally, this study includes a core set of CSF indicators that could guide managers and policy-makers to more climate-smart practices, enhancing climate adaptation of forests and the provision of ecosystem services. Central indicators promote forest biodiversity conservation and sustainable management of forest resources that fit with the demand of both the forest sector and wider public.

Jandl et al. (2018) conclude that the production of long living wood products (i.e., construction timber) is a favourable strategy for CSF wherein carbon is stored in longer standing trees and products. This supports the centrality of the wood consumption indicator, which takes into account the use of wood and the types of products that would be favourable to CSF. However, some issues are related to the risk to long-term standing trees from episodic disturbances and the fact that long-standing timber slows carbon capture in comparison to new forests (Harmon and Campbell, 2017; Jandl et al., 2018). The relationship between tree carbon and resulting soil carbon capture is viewed as positive for CSF even though tree carbon capture slows with time, soil carbon is generally recognised to increase. In spite of this widely accepted view, Ji et al. (2017) present evidence for accumulation of soil carbon peaks in temperate broadleaf forests in stands around 50 years of age during the pre-mature stage, with general decreases thereafter. This further emphasises the importance of adapting CSF recommendations to regional or local context. Scenarios of CSF are based upon trade-offs and decision-making processes, suitable to the socio-economic systems and ecological lifecycles. As an example, early thinning can be viewed as an integral stage of forest production to supply bioenergy (woodfuel), substituting the use of fossil fuels, while supporting growth of higher quality and economically valuable final timber crop (roundwood) (Bowditch et al., 2019; Jandl et al., 2018; Röser et al., 2011). Managing woody biomass, for example, may reduce the risk of large catastrophic wildfires and alter the flow rates of watercourses during extreme weather conditions (droughts, heat waves, rainstorms and strong winds) to reduce flooding risk. The potential impact of a wood energy indicator through management and use would explain the importance within the network analysis.

Developing CSF resources to contextualise the indicators, especially at a local level, will require collection of data from long-term monitoring plots, creation of new plots to evaluate targeted attributes at both the stand and landscape level, which will enable the analyses of trends in CSF indicators to identify priority areas for adaptation and mitigation. Trends in CSF indicators could also be mapped out through the trajectory of scenarios that either implement CSF or alternative management actions (Yousefpour et al., 2010). Other tools, such as the European network of marteloscope sites, are being used to gather historic and baseline data, as well as being deployed for forestry training activities (Santopuoli et al., 2019). These sites have the potential to play a crucial role in testing SFM indicators through the simulation of various forestry scenarios, as well as maintaining and evaluating time series data from sites that quantify vulnerability to climate change.

Mina et al. (2017) observed that climate change projections under different management scenarios have highly variable impacts on the provision of ecosystem services in mountains areas, subject to regional and site conditions, as well as future climate responses. Therefore, establishment of connected and comparable demonstration sites and permanent forest plots focused upon collection of CSF indicator data over geographically distributed areas will aid monitoring of vital climate change impacts on forest ecosystems (e.g., Instruction on Site Characteristic in measurements in Forests (ICOS)). Nevertheless, long-term plots can only approximate certain trade-offs without greater accountability of disturbances and pressures that change responses (Locatelli et al., 2017). In some areas, such as mountain regions, vulnerability to climate change and everyday pressures will place forestry at the centre of an integrated social-ecological support system that enhances economic opportunity and boosts resilience to the uncertainty of climate induced changes (Schultz et al., 2015). Therefore, planning and management strategies would benefit from co-development with local populations to ensure investment and recognition of human-forest key relationship.

4.2. Implementation

Each country and region will interpret definitions, principles and indicators differently, as diverse forest types and tree species, ecosystems, socio-economic conditions, and people will vary. These will be especially prevalent in critical or more sensitive areas, such as European mountains (Lexer and Bugmann, 2017). As the need for action against climate change heightens, greater guidance will be needed at all scales from international policy to individual forest managers. A keystone development to bridging the gap between policy and practice will be effective engagement with forest managers, forest communities and different forest owner types to assess the accessibility of CSF indicators. Implementing locally adapted CSF through diverse interactive methods aims to help sustainable communities develop alongside a productive forest resource. Andersson and Keskitalo (2018) state that actions must be achieved through social rather than environmental logics, as internal institutional systems, motivations and incentives will often steer and limit adaptation conceived by external drivers and influences. Mitigation strategies that dominate high-level policy should be balanced and aligned with development of lower level actions, so regional nuance of both the culture and managed environment are captured, and reflected in '*applied or working'* policy. Additionally, over-dependency on carbon sequestration and storage as a panacea to climate-induced changes could seriously overshadow adaptive capacity on regional and local scales inhibiting small innovations and planning strategies that could contribute cumulatively to the global issue (Bull et al., 2018; Frame et al., 2018; Thornton and Comberti, 2017).

CSF adaptation measures can include the aim to improve management of specific species mixtures to maintain production under a changing climate, as well as maintaining or increasing associated biodiversity (Del Río et al., 2016, 2014; Nabuurs et al., 2018; Pretzsch et al., 2017), which could simultaneously support the social dimensions of these forests for resilient communities (Armatas et al., 2016; Brunner and Grêt-

Regamey, 2016; Seidl et al., 2016). A mixed species approach can be used to buffer but not entirely protect against conditions resulting from climate change, however, the complementarity of mixed species outperforms block mixtures under most climate change scenarios (Paul et al., 2019). Many forests will be in vulnerable climatic zones with concentrated climate induced changes impacting species mixes, habitat suitability and ultimately shifting distribution ranges. Nevertheless these changes may favour and provide new production opportunities for some regions (Lindner et al., 2014). This may represent an important revenue source for local economies, especially for communities suffering from depopulation, as well as a lack of services and infrastructure (structural and business) that supports community development. However, most predictions cite the reduction of species range and consequently lower production as more probable (Liang et al., 2016), which makes conservation and enhancement of current native forest mixtures important.

One way of furthering resilience and adaptability of native forest diversity is to improve connectivity and migration corridors of key species and forest structures to sustain the availability of seed sources, as well as genetic variation (Yang et al., 2015). Such adaption and response to climate induced change embraces the multifunctionality of forests, which must be reflected in management approaches and cultural integration (Halofsky et al., 2018). In Finland, forest owners show a willingness to participate in PES schemes aimed at reducing wider-landscape risks of pests and diseases, as long as it provides some management flexibility and does not unnecessarily prohibit forest operations that produce revenue and improved end crop yields (Sheremet et al., 2018). This approach demonstrates a step towards customising PES to fit individuals and regional differences through a common goal that binds forest owners over large landscapes (Curtin, 2014). A similar tailored PES model could be used for CSF guided by indicators and local priorities that taps into important issues for managers.

CSF mitigation focusses upon carbon sequestration and storage, timber product use, bioenergy growth and use, and the interactions between lifecycles to optimise carbon neutral activity. Therefore, reconciling and aligning these sometimes-competing activities will be a crucial step. However, the focus on tangible metrics currently dominating the CSF (Nabuurs et al., 2018, 2017) could be a limiting factor in developing future CSF strategies. Carbon sequestration is a now widely accepted substantive mitigation mechanism, as trade-offs in decision-making and resultant management activities are measurable, such as yield increment, revenue variability and the use of various silvicultural approaches. Greater recognition of forest planning and diverse forestry approaches in mitigation strategies should be integrated into CSF. In fact, these actions underpin carbon sequestration and storage, as well as adaptation issues, which will cumulatively impact the rest of the supply chain and forest-dependent communities who are supported economically and socially by a range of ecosystem services (Brang et al., 2014; Colloff et al., 2016; Nagel et al., 2017).

Ecosystem services assessment has been identified as a tool that could link stakeholders with management practices and CSF governance, a visible action and beneficial outcome that strongly relates to social dimensions of CSF. Therefore, PES, conservation partnerships and bridging organisations with local stakeholder expertise could play an important capacity building role (Cockburn et al., 2016; Lange et al., 2016; Rouillard et al., 2015). Creating and maintaining social capital, such as knowledge exchange, upskilling, technological development and use, as well as better monitoring and reporting to aid adaptive learning (Curtin, 2014; Lawrence, 2017) could be key components of assessing the social dimensions of CSF. The CSF definition and subsequent development of applicable C&I guidance aim to support livelihoods of sustainable communities based on production, conservation and well-being.

Key features to creating an implementation pathway for CSF should include management and connectivity of large datasets for long-term monitoring to track and understand the biophysical processes and changing trends. These features will be supported by openly accessible data, guidance on use, and landscape scale data that can distil into customisable tools for managers, as well as into coherent points of collaboration and transparency between policy and practice (Nabuurs et al., 2019).

4.3. Perspectives

European policy should aim to be comprehensive and flexible enough to include broad actions and strategies with locally tailored solutions for regions and individual countries. A survey by Sousa-Silva et al. (2018) explored forest managers views on climate change over seven European countries. These managers recognised the potential impact of climate change but had little awareness of how to respond to threats or implement adaptive management measures. This is supported by Coll et al. (2018) who's work identified forest managers lack of knowledge regarding adaptability and trade-offs to environmental change in mixed-species forests. A CSF toolkit that uses the definition and indicators identified through the analysis presented here could be used as a base to address the knowledge/information gap between science and practice.

Developing CSF from the bottom-up using experience of forest managers will be central to shaping best practice from current adaptive management implementation and applied learning. On the international level, forestry is increasingly viewed as one of the most effective ways to mitigate climate change (Bastin et al., 2019; Chazdon and Brancalion, 2019; FAO, 2010b), however, the discussion between forest accounting being based upon past management activities and prospective management is ongoing (Grassi et al., 2018). Establishing different management approaches that deviate from the status quo has been challenging in regard to PES, as integrating clear and trusted verification processes and documenting an agreed baseline from where alternative management diverges is difficult to implement on a wide-scale (Kang et al., 2019). In this context an appropriate mix of traditional and novel indicators of climate change impacts on European forests have been proposed to improve the prediction of stand dynamics and forest productivity (Bussotti and Pollastrini, 2017). Under the Paris Agreement a flexible approach toward baseline accounting of past management that supports changes that increase production, forest health and forest community resilience, would reflect a middle ground or best of both world's scenarios.

Mismatches in communication and failed initiatives often originate from narrow scope and a lack of vital information. Therefore, combining social sciences with more traditional areas of forest science could help avoid issues that perpetuate problems (Duckett et al., 2016). Recognising and integrating novel factors such as social territories and scales, based upon core social-ecological systems, could identify key intervention points that help enhance our ability to manage forests and avoid future spatial, temporal and political mismatches (Fischer, 2018). In Melnykovych et al. (2018) community members showed interest in designing and implementing the sustainable forest policy measures that managed the provision of ecosystem services and enhanced well-being. However, these aspirations were tempered by the need to prioritise income generation and daily management actions. This underlines the need to develop resilience with local community sustainable development goals, as well as balance long-term policy goals with short-term needs of the locality (Bull et al., 2018). An approach that operates through co-design and production may have a greater chance of creating CSF framework with bespoke set-ups for different regions, ownership and forest types.

CSF definitions, guidance and tools generated by such projects as CLIMO could help refine the approach to forestry as a more sophisticated mitigation measure encouraging socio-economic growth and innovation. CSF should endeavour to take a systemic approach rather than treating individual symptoms, looking to the long-term health and resilience of forest ecosystems, which includes people as a central component.

Ollikainen (2014) states that the EU Bioeconomy Action Plan fails to take account of the forestry sector's link to climate change and superficially addresses the land use management dynamics that are vital for developing climate-smart policy. Such criticism highlights crucial gaps in the connectivity of European strategies (Forestry, Bioeconomy, and Climate etc.) that could potentially be addressed and informed by further developed CSF definitions, guidelines and toolkits, which aim to enhance the science/policy interface. However, Hodge et al. (2017) emphasises that bioeconomy already acts as a bridging concept, bringing forestry and climate change closer together rather than dividing them into separate branches that operate in isolation. Using an umbrella concept, such as bioeconomy, which can be inclusive and comprehensive, can also embed broad-bush approaches that overlook key implementation issues in specific sectors.

Additionally, such concepts as bioeconomy are dominated by economic, resource use and commodity concerns, which have the tendency to neglect social and ecological considerations (Karvonen et al., 2017), such as high-level governance and local participation (Pülzl et al., 2014). These have been recognised as key elements of the CSF approach and, therefore, should be highlighted as important considerations for translating bioeconomy impacts into relatable regional versions. Bioeconomy could be an important concept in halting the reduction of biodiversity and ecosystem services flows, which rely on balancing the effective integration of social-ecological, cultural and economic dimensions alongside the management of natural resources that are subject to uncertain changes (Marchetti et al., 2014). Therefore, CSF as defined here, offers a legitimate and inclusive discourse linking energy, carbon, production, biodiversity conservation and resilient communities; supported by scientific evidence and metrics that can provide implementation options and guide management goals. Market inclusion and transparency of climate impact and risk to key environments from increasing climate-induced changes will be crucial to avoiding economic recession, therefore markets need to take more responsibility and support PES and CSF or risk further loss of vital ecosystem services (Griffin, 2020). To achieve such goals specific evidence and management roadmaps are needed to give policy the necessary teeth to affect wide-ranging change that will reach and work with individual forest managers.

4.4. Limitations and future work

When approaching any type of definition or guidance for a wide range of stakeholders over large geographical areas there will be limitations, as well as scope for improvement and further development. Strengthening our definition and set of indicators for CSF will be the next steps, as the participatory process was represented by a group of mostly forest research professionals, although these were geographically dispersed with a range of expertise, which substantiates the broad European approach. Including forestry industry professionals and practitioners in the refinement of the definition and indicators is the next step and currently forest managers and professionals in 20 countries of the CLIMO network are responding to the CSF definition and indicators to inform the next iteration and potential steps for tailoring at regional levels.

Aligning the CSF indicators with available data from European forest monitoring networks and National Forest Inventories data will allow for creation of baselines and historical analysis of trends toward climate smartness and the corresponding management actions. Lorente et al. (2018) created a web-based platform to display and communicate a set forest indicators for climate change. However, they acknowledged further refinement at the regional level and greater consideration of socio-economic factors, as well as partnership and engagement with practitioners would enhance the impact and utility of the indicators. Indicators for the transition from a federal to a hybrid social forestry governance structure in the USA were developed focussing upon partnership, collaboration and institutional innovations (Abrams et al., 2019). This work provides the opportunity to map changes in governance patterns of forest units over spatial and temporal scales but also allows for analysis of capacity building and institutional infrastructure required to support these transitions. However, the authors also recognised the importance of understanding how changes in governance influenced and impacted ecological change to enhance the stewardship function increasing resilience and ecological integrity (Cannon et al., 2018). Such steps will be key for CSF to establish a sound platform of communication and dissemination between practice and policy, shaping clear linkages that can be understood and interpreted by both managers and policy-makers.

Finer detail of data collection to recognise the importance of local management systems that work within SFM indicators has been highlighted in northern Italy by demonstrating the complex socio-economic dynamics of coppice management systems that support a historic and wider economy (Riccioli et al., 2019). Despite the peripheral location of cultural indicators in this paper the definition reconciles the importance of social dimensions including socio-economics in supporting and promoting CSF. Further work around cultural and socio-economic indicators will be required perhaps as a linking sub-set of indicators that facilitates the key channel of communication between managers and policy-makers.

5. Conclusion

Promoting CSF will require more time to build effective working relationships between stakeholders and policymakers cultivating the trust needed to realise these strategies, recommendations and best practice guidance (Lange et al., 2016). Improved communication and use of expansive participatory methods to engage and interact with forest managers will play a key role in this process and naturalising what may be seen by many, as "*another recycled concept*" into practice and common vocabulary of the practitioner. Advancing CSF processes, beginning with baseline definitions, testing of indicators through key sites, monitoring and experimental data will be influential in developing and progressing climate change policy, such as the Paris Agreement. This paper offers a potential roadmap and process to implementing CSF starting from the definition and indicators with the aim of expanding our understanding of management and decision-making challenges that can be ultimately refined into tool that delivers on SFM goals. This paper is an important first step in offering a CSF definition and indicators that can be used as a template on a European level and adapted to localities to provide much needed guidance for managing more resilient forests and practicing CSF. However, engaging forest managers and wider stakeholders of forest communities will be central to developing, testing and refining further steps that aim to produce a valuable resource for forest practitioners to enhance the management of their forests in response to future uncertainty and growing demands on these forests.

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List of captions of figures and tables

Figure 1 – Process, and interaction within the CLIMO project, for building consensus on definitions of CSF in mountain regions. The iterative deliberative process conducted in CLIMO with a confrontation stage that engaged all working groups to account for any issues, difference of opinions and new information.

Figure 2 – Network analysis of CSF indicators relevance to adaptation and mitigation. The map shows the suitable indicators for assessing climate-smart forestry in mountain ecosystems. This map represents the merged map considering both, adaptive and mitigation issues, according the point of view of CLIMO participants. Indicators are clustered in core and peripheral groups in order to display their relevant importance to provide information about the climate-smartness of forests.

Figure 3 – Schematic representation of primary and secondary, core and peripheral, groups of indicators useful to assess and to support the development of climate-smart forestry management guidelines (Climate eye diagram). Black circle are the main themes/threads that support CSF and their indicators

Table 1 – Set of Indicators for SFM selected from the Forest Europe C&I set (https://foresteurope.org/sfm-criteria-indicators/), considered suitable for assessing the provision of ecosystem services, according the view of CLIMO participants. New 4 indicators have been included during the CLIMO project meetings.

Table 2: Ecosystem Services selected from CICES database (CICES classification, version4, 2012; https://cices.eu) and considered useful to monitor and assess Climate-Smart Forestry, according the view of CLIMO participants.

Table 3 - Centrality values. Degree is the number of ties that link each indicator with forest ecosystem services; Betweenness represents the number of times one indicator in the network is "between" other indicators on the causal paths. Closeness calculates the farness and normalized closeness centrality and variants of each vertex and gives the overall network closeness centralization. K-core is a maximal group of actors, all of which are connected to some number (k) of other members of the entity. Group show the cluster identified in this study, based on the centrality values and position of nodes in the network.

Figure 1

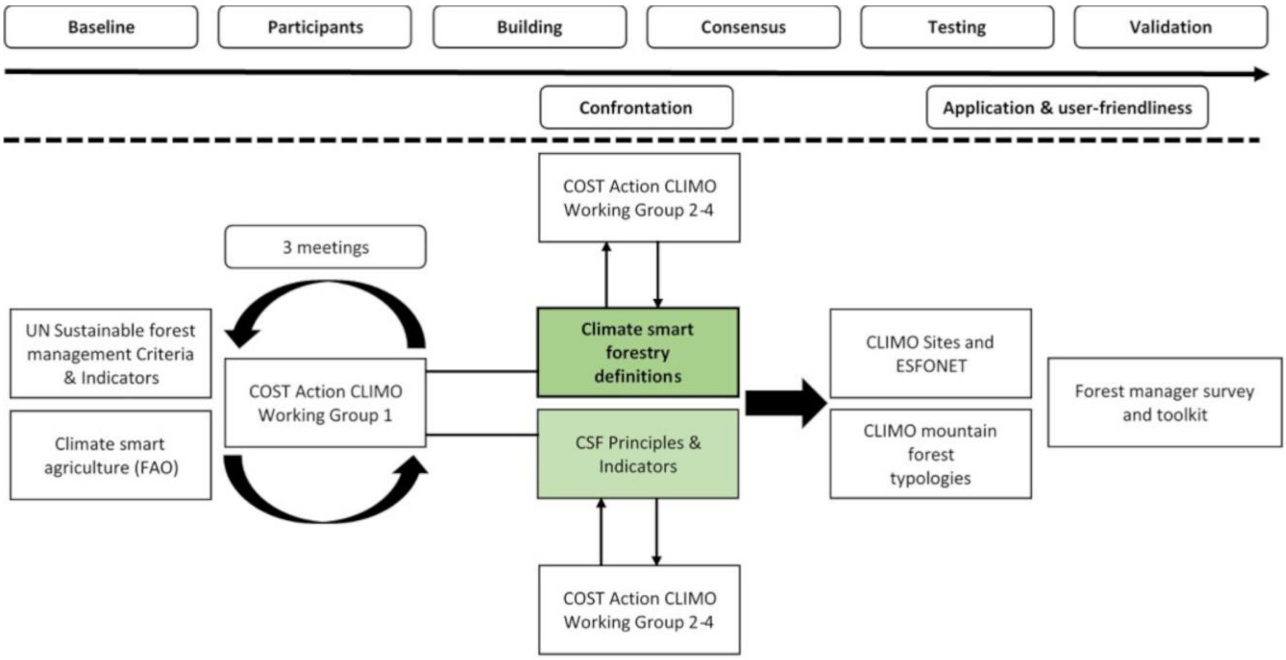

Figure 2

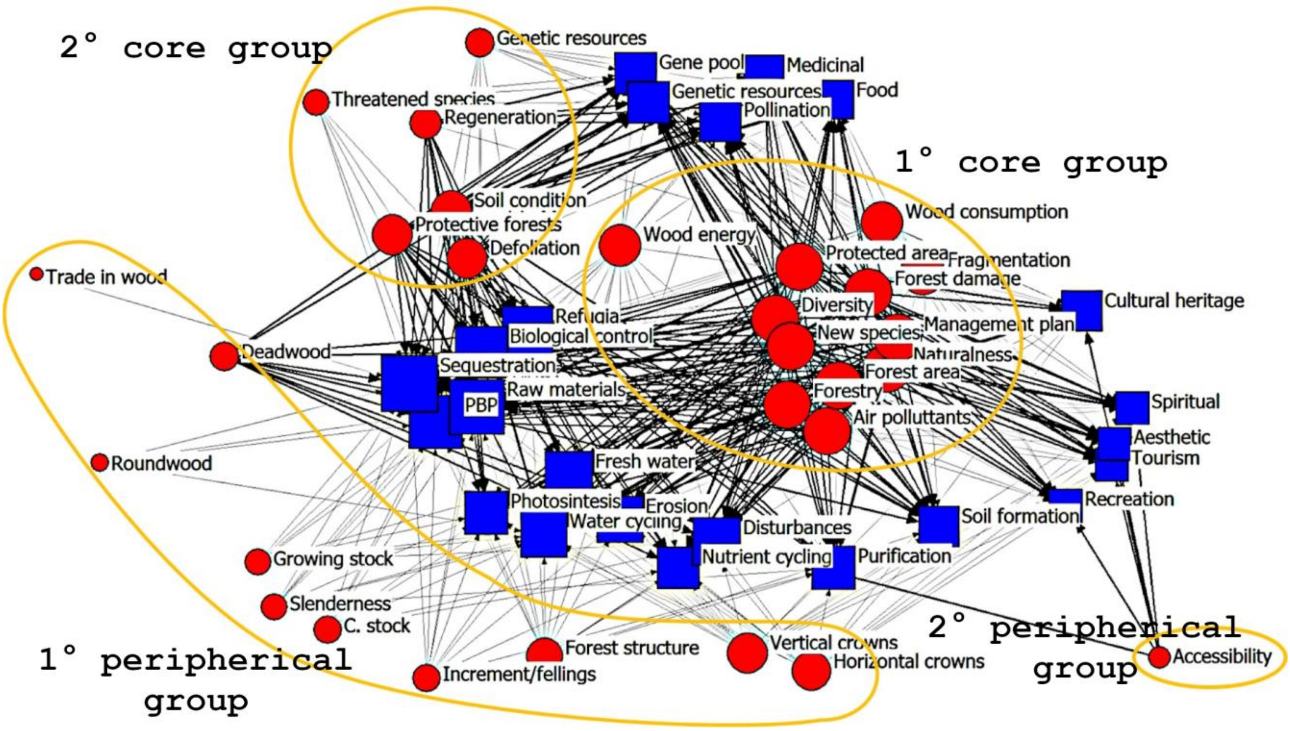

Figure 3

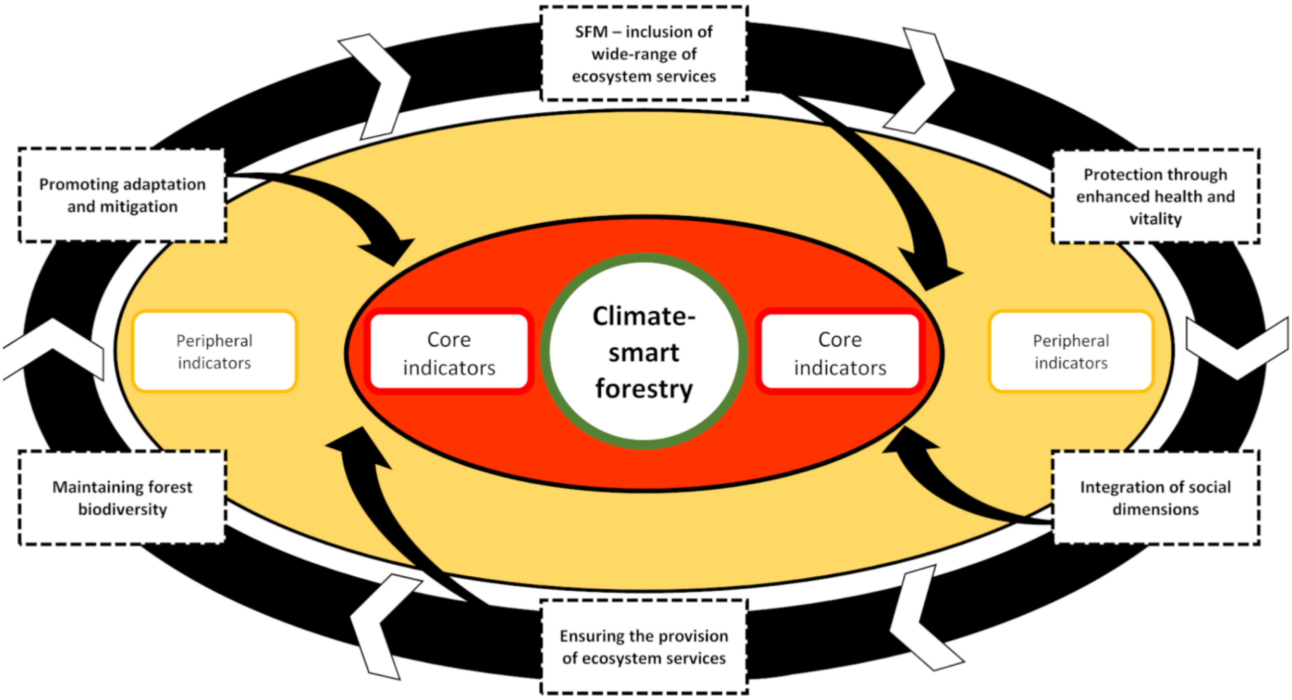
SFM – inclusion of wide-range of ecosystem services
Promoting adaptation and mitigation
Protection through enhanced health and vitality
Peripheral indicators
Core indicators
Climate-smart forestry
Core indicators
Peripheral indicators
Maintaining forest biodiversity
Integration of social dimensions
Ensuring the provision of ecosystem services

Table 1: Set of Indicators for SFM selected from the Forest Europe C&I set (https://foresteurope.org/sfm-criteria-indicators/), considered suitable for assessing the provision of ecosystem services, according the view of CLIMO participants. New 4 indicators have been included during the CLIMO project meetings. Nine indicators were not selected (3.3 No-wood goods; 3.4 Services; 6.1 Forest holding; 6.2 Contribution of forest sector to GDP; 6.3 Net revenue; 6.4 Expenditures for services; 6.5 Forest sector force; 6.6 Occupational safety and health; 6.11 Cultural and spiritual values).

Criteria	**Indicator name**	**Label**	**Description (**based on the MCPFE 2002 & Madrid 2015**)**
C1: Forest Resources and Global Carbon Cycles	1.1 Forest area	**Forest area**	Area of forests and other wooded land, classified by forest type and by availability for wood supply, and share of forest and other wooded land in total land area
	1.2 Growing stock	**Growing stock**	Growing stock on forest and other wooded land, classified by forest type and by availability for wood supply
	1.3 Age structure and/or diameter distribution	**Forest structure**	Age structure and/or diameter distribution of forest and other wooded land, classified by availability for wood supply
	1.4 Carbon stock	**Carbon stock**	Carbon stock and carbon stock changes in forest biomass, forest soils and in harvested wood products
C2: Forest Health and Vitality	2.1 Deposition of air pollutants	**Air pollutants**	Deposition and concentration of air pollutants on forest and other wooded land
	2.2 Soil condition	**Soil condition**	Chemical soil properties (pH, CEC, C/N, organic C, base saturation) on forest and other wooded land related to soil acidity and eutrophication, classified by main soil types
	2.3 Defoliation	**Defoliation**	Defoliation of one or more main tree species on forest and other wooded land in each of the defoliation classes
	2.4 Forest damage	**Forest damage**	Forest and other wooded land with damage, classified by primary damaging agent (abiotic, biotic and human induced)
C3: Forest Biological Diversity	3.1 Increment and felling	**Increment/felling**	Balance between net annual increment and annual felling of wood on forest available for wood supply
	3.2 Roundwood	**Roundwood**	Quantity and market value of roundwood
	3.5 Forests under management plans	**Management plan**	Proportion of forest and other wooded land under a management plan or equivalent
C4: Forest Biological Diversity	4.1 Tree species composition	**Diversity**	Area of forest and other wooded land, classified by number of tree species occurring
	4.2 Regeneration	**Regeneration**	Total forest area by stand origin and area of annual forest regeneration and expansion
	4.3 Naturalness	**Naturalness**	Area of forest and other wooded land by class of naturalness (“undisturbed by man”, by “semi-natural” or by “plantations”)
	4.4 Introduced tree species	**New species**	Area of forest and other wooded land dominated by introduced tree species

C4: Forest Biological Diversity	4.5 Deadwood	**Deadwood**	Volume of standing deadwood and of lying deadwood on forest and other wooded land
	4.6 Genetic resources	**Genetic resources**	Area managed for conservation and utilisation of forest tree genetic resources (in situ and ex situ genetic conservation) and area managed for seed production
	4.7 Landscape pattern	**Fragmentation**	Area of continuous forest and of patches of forest separated by non-forest lands
	4.8 Threatened forest species	**Threatened species**	Number of threatened forest species, classified according to IUCN Red List categories in relation to total number of forest species
	4.9 Protected forests	**Protected area**	Area of forest and other wooded land protected to conserve biodiversity, landscapes and specific natural elements, according to MCPFE categories
C5: Protective Function (Soil and water 5	5.1 Protective forests - soil, water and other ecosystem functions, and infrastructures	**Protective forests**	Area of forest and other wooded land designated to prevent soil erosion, preserve water resources, maintain other protective functions, protect infrastructure and managed natural resources against natural hazards
C6: Socioeconomic Functions	6.7 Wood consumption	**Wood consumption**	Consumption per person of wood and products derived from wood
	6.8 Trade in wood	**Trade in wood**	Imports and exports of wood and products derived from wood
	6.9 Energy from wood resources	**Wood energy**	Share of wood energy in total primary energy supply, classified by origin of wood
	6.10 Accessibility for recreation	**Accessibility**	The use of forests and other wooded land for recreation in terms of right of access, provision of facilities and intensity of use
New indicators added by CLIMO participants	Management system	**Forestry**	Forest area classified according the silvicultural system adopted: coppice system; even-aged system (clear cut or shelterwood), uneven-aged system (selection system)
	Slenderness coefficient	**Slenderness**	The ratio of tree total height to diameter outside bark at 1.3 m above ground level
	Vertical distribution of tree crowns	**Vertical crowns**	Distribution of tree crown in the vertical space. It can be measure in terms of layers (one, two, multiple), or in terms of ratio between tree height and crown length.
	Horizontal distribution of tree crowns	**Horizontal crowns**	Canopy space filling and can be expressed in measure of density of tree crowns, such as crown area, tree crown diameter. It can be also expressed in measure of density of trees, such as trees per hectare, basal area per hectare (in this case the horizontal distribution refers to the tree).

Table 2: Ecosystem Services selected from CICES database (CICES classification, version4, 2012; https://cices.eu) and considered useful to monitor and assess Climate-Smart Forestry, according the view of CLIMO participants.

Ecosystem service	Label	CICES Section	CICES Division
Recreation and mental and physical health	**Recreation**	Cultural	Intellectual and experientially
Tourism	**Tourism**		Symbolic
Aesthetic appreciation and inspiration for culture, art and design	**Aesthetic**		Symbolic
Spiritual experience and sense of place	**Spiritual**		Symbolic
Protection of cultural heritage	**Cultural heritage**		Symbolic
Primary biomass production	**PBP**	Provisioning	Materials
Food	**Food**		Nutrition
Timber, fuel, fibre	**Raw materials**		Materials
Fresh water	**Fresh water**		Nutrition
Pharmaceuticals and bio-chemicals	**Medicinal**		Materials
Genetic resources	**Genetic resources**		Materials
Production of atmospheric oxygen	**Photosynthesis**	Regulating	Regulations biotic environment
Soil formation and retention	**Soil formation**		Regulations physical environment
Nutrient cycling	**Nutrient cycling**		Regulations biotic environment
Water cycling	**Water cycling**		Flow regulation
Maintenance of genetic diversity	**Gene pool**		Regulations biotic environment
Habitats for species	**Refugia**		Regulations biotic environment
Purification of water and air	**Purification**		Wastes regulation
Carbon sequestration and storage	**Sequestration**		Regulations physical environment
Moderation of natural disturbances, e.g., flood alleviation	**Disturbances**		Flow regulation
Erosion prevention and maintenance of soil health	**Erosion**		Flow regulation
Pollination	**Pollination**		Regulations biotic environment
Biological control	**Biological control**		Regulations biotic environment

Table 3: Centrality values. Degree is the number of ties that link each indicator with forest ecosystem services; Betweenness represents the number of times one indicator in the network is "between" other indicators on the causal paths. Closeness calculates the farness and normalized closeness centrality and variants of each vertex and gives the overall network closeness centralization. K-core is a maximal group of actors, all of which are connected to some number (k) of other members of the entity. Group show the cluster identified in this study, based on the centrality values and position of nodes in the network.

Selected indicator	Degree	Betweenness	Closeness	K-core	Group
1.1 - Forest area	23	30.1	79	14	1st-core group
2.1 - Deposition of air pollutants	23	30.1	79	14	1st-core group
2.4 - Forest damage	23	30.1	79	14	1st-core group
3.5 - Management plan	23	30.1	79	14	1st-core group
4.1 - Diversity	23	30.1	79	14	1st-core group
4.3 - Naturalness	23	30.1	79	14	1st-core group
4.4 - New species	23	30.1	79	14	1st-core group
4.9 - Protected forests	23	30.1	79	14	1st-core group
(Climo) - Forestry	23	30.1	79	14	1st-core group
4.7 - Fragmentation	21	25.2	83	14	1st-core group
6.7 - Wood consumption	19	20.9	87	14	1st-core group
6.9 - Wood energy	19	17.3	87	14	2nd-core group
2.2 - Soil condition	18	15	89	14	2nd-core group
2.3 - Defoliation	18	15	89	14	2nd-core group
5.1 - Protective forests	18	15	89	14	2nd-core group
(Climo) - Vertical crowns	18	18.3	89	14	1st-peripheral group
(Climo) - Horizontal crowns	17	16.5	91	13	1st-peripheral group
1.3 - Forest structure	15	10.1	95	14	1st-peripheral group
4.2 - Regeneration	13	7.8	99	13	2nd-core group
4.5 - Deadwood	11	5.2	103	11	1st-peripheral group
4.6 - Genetic resources	11	5.5	103	11	2nd-core group
1.4 - Carbon stock	10	3.9	105	10	1st-peripheral group
3.1 - Increment/fellings	10	3.8	105	10	1st-peripheral group
1.2 - Growing stock	9	3	107	9	1st-peripheral group
4.8 - Threatened species	9	3.2	109	9	2nd-core group
(Climo) - Slenderness	9	2.9	109	9	1st-peripheral group
6.1 - Accessibility	6	1.4	121	6	2nd-peripheral group
3.2 - Roundwood	4	0.5	119	4	1st-peripheral group
6.8 - Trade in wood	1	0	125	1	1st-peripheral group

Box 1 – *Climate-Smart Forestry in mountain regions definition*

Climate-smart forestry *is sustainable adaptive forest management and governance to protect and enhance the potential of forests to adapt to, and mitigate climate change. The aim is to sustain ecosystem integrity and functions and to ensure the continuous delivery of ecosystem goods and services, while minimising the impact of climate-induced changes on mountain forests on well-being and nature's contribution to people.*

Adaptation measures of forests that maintain or improve their ability to grow under current and projected climatic conditions and increase their resistance and resilience. The adaptive capacity to changes in climate and to the timing and size of climate-induced disturbances (e.g., fire, extreme storm events, pests and diseases) can be enhanced by promoting genetic, compositional, structural, and functional diversity at both stand and landscape scales. This includes facilitating natural regeneration and planting of native as well as non-native tree species, genetic variants and individuals that are considered to be adapted to future conditions. Increased connectivity assists the migration of forest species.

Mitigation of climate change by forests is a combination of carbon sequestration by trees, carbon storage by forest ecosystems, especially soils, and forest derived products, such as structural timber, and by carbon substitution - directly by replacing fossil fuels with bioenergy and indirectly through use of wood to substitute for higher carbon footprint materials.

The ***social dimension*** of forestry holds many aspects, from the involvement of stakeholders from local communities, and their conflicts over land use or for the access to skills and technology, to global forest governance challenges. Climate change may jeopardize forest ecosystem functioning and brings social and economic consequences for people, which may modify priorities of ecosystem services at various scales. Assessment for ecosystem services could be a tool making this process more efficient with respect to indicators relevant for governance regime and actors involved.

In summary, **climate-smart forestry** should enable both forests and society to transform, adapt to and mitigate climate-induced changes.

Supplementary material

Appendix A: Synthesis of the “climate-smart forestry” literature review

The road to CSF concept

Publications involving the search parameters of ‘Climate-Smart Forestry’ in the Web of Science database, accounts for 106 publications since 2000 (Figure S1).

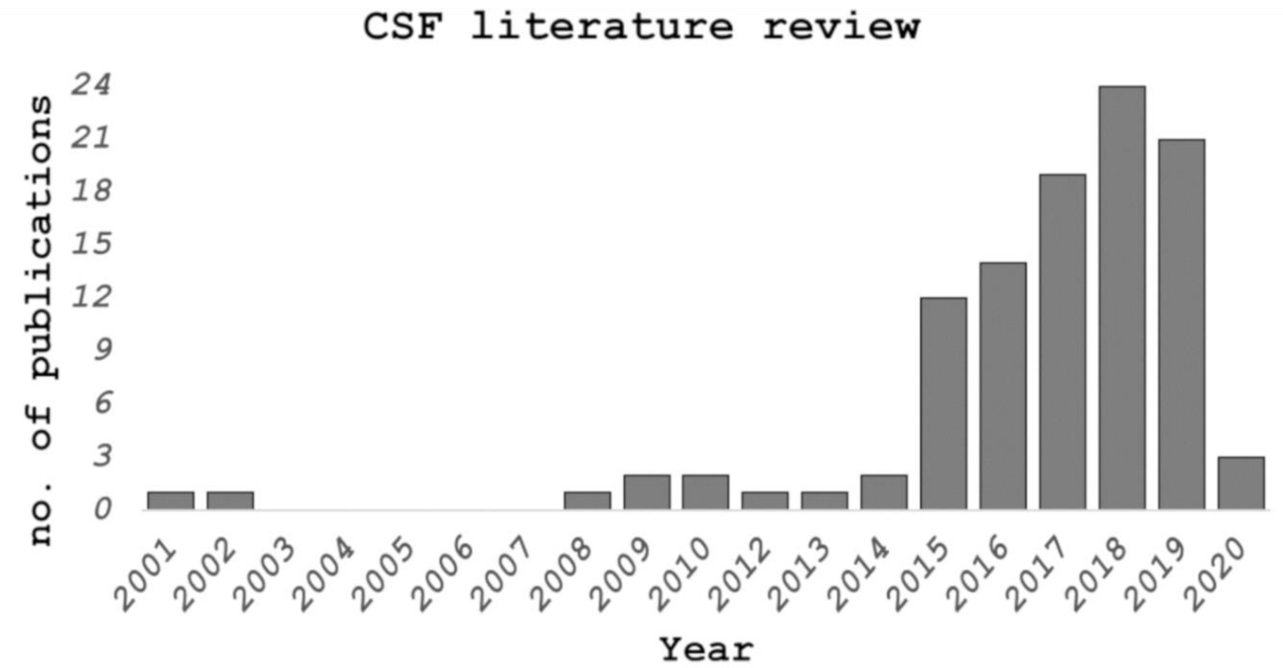

Figure S1: Number of publications from 2001-2019 that include ‘Climate-Smart Forestry’ as search terms in Web of Science. Various searches (Scopus, google scholar, Web of science) has yielded different results, ranging from 82 – 106 publications using the same search parameters. Date search performed: 03/03/2020.

Nitschke and Innes (2008) model the response of forest ecosystem structure to potential fire regimes and species under climate-induced changes, highlighting the need to integrate climate-smart strategies into forest management planning and application. Jantke et al. (2016) compare Natura 2000 sites with levels of soil carbon and agricultural land values, which show a correlation between low land values and high soil carbon content and argue that such criteria could be a template for climate-smart conservation strategies. However, this study restricts the interpretation solely to agricultural values and thus omits wider economic, environmental and social potential. Yang et al. (2015) focus on the potential impact of species ‘*adaptational lag*’ to changes in and maintaining the productive stock and genetic variety of black spruce

(*Picea mariana* (Mill.) BSP.); they emphasise that important mixed forest structures can be achieved through targeted climate-smart seed movements that mitigate against slow or unresponsive adaptation processes. Halofsky et al. (2018) strongly advocate climate-smart strategies that facilitate rapid practical implementation, in response to the increasing frequency of extreme events.

Acceptance and adoption of climate-smart strategies and responses are dependent on people that drive policy, implement management and communities that rely on forests services. The potential for both disruption and enhancement of the socio-economic landscape is wide-ranging. However, transnational forest policy continually fails to connect to the local working realities, which are critical for developing coherent policies that can adapt to the diversity and complexity of local contexts (Bull et al., 2018). Winkel and Sotirov (2016) highlight that forest policy suffers from symbolic rhetoric to serve sectoral interests (economic and institutional competition) but rarely achieves any substantive progress. Common pathways to realising change focusses on socio-ecological systems by connection to local ecosystems, promoting dialogue between stakeholders, fostering social innovation and providing an institutional framework to facilitate new structures (Biggs et al., 2010).

Socio-ecological systems can be viewed as a way to release economic and social potential (Fischer, 2018), however, effective indicators for social values and cultural ecosystem services are still undeveloped and difficult to assess (Maes et al., 2016). Social values can be used indicatively within specific spatial areas and help establish main priorities but usually require further clarification and verification (Chan et al., 2012; Tenerelli et al., 2016). However, such approaches could provide a frame for effective social indicators on a landscape level. Much like ecosystem management, CSF is underpinned by the interactions between various dynamic components aiming to interlink at multiple levels and facilitating transformation through more adaptive, integrated and collaborative approaches (Folke et al. 2010). As forest managers, policy-makers and the wider population are central to promoting and developing the CSF process through socio-ecological systems, participatory decision-making and social-innovation are considered crucial pathways to achieving these aims (Biggs et al. 2010). Greater expansion of socio-ecological systems and CSF will continue with the emergence of new knowledge and problems, therefore the scope of CSF should be responsive, as well as planned to best adapt to specific needs when time arrives. Blattert et al. (2017) acknowledge that forest managers require appropriate management strategies to produce diverse services that the public require. They weighted their indicators to represent management functions considered more important in a local or regional context, such as mountain forests, and recognised the protective function as the highest priority. This approach provides a basic flexibility to take into account more area-specific requirements and changing management objectives over diverse landscapes. However, this approach should be investigated further to refine and expand the flexibility.

In summary, these papers on CSF highlight the need for collaboration across boundaries and over large spatial scales to ensure the productivity and functionality of forests into the future (Anton et al., 2010; Curtin, 2014; Johansson, 2016). Aligning climate-smart characteristics of forestry with management practices and communicating clear methods to managers remains an elusive step for integrating climate change management responses with current management and guidance. Addressing these gaps is integral to this project, as well as recognising the current shortfall of work around social-ecological systems of CSF, which is a key feature in harmonising new management approaches and knowledge into current systems.

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Appendix B

Table S1: List of CLIMO meetings related to development of definition and indicators

Meeting	Date	Action	Comments
Trento, Italy	February, 2017	Identification of a sub-group to work on definition of Climate-Smart Forestry. First discussion of three components, comprising mitigation, adaptation and social dimensions.	Membership of definitions sub-group commenced with those expressing a strong interest in participation, but continued with filling of gaps in the composition. For example, ensuring that experts representing other Working Groups (not just Working Group 1) were included.
Sofia, Bulgaria	September, 2017	Three-day workshop to establish an initial definition of Climate-Smart Forestry. Sub-group included Chair, Vice Chair and Project Manager, Working Group 1 Leader and members of the other Working Groups.	A one-page initial draft definition was prepared. Contribution at this stage led to co-authorship of definition.
Virtual (email)	October, 2017 - February, 2018	One-page initial draft definition shared for comment and amendment with entire COST Action.	Contributions at this stage resulted in amendments to the draft and inclusion in co-authorship.
Sofia, Bulgaria	February, 2018	Working Group 1 sub-group refinement of draft and presentation to Open Meeting for further/final criticism and amendment.	A contribution at this stage that resulted in amendment to the draft brought inclusion in co-authorship.

Table S2: List of participants which attended to the meetings. In bold the co-authors of the manuscript.

Surname	Name	Country	Background	Trento Feb-17	Sofia Sept-17	Virtual Oct-17-Feb-18	Sofia Feb-18
Antonucci	Serena	Italy	Forest ecology	x			
Azevedo	Joao	Portugal	Forest economics				x
Bielak	Kamil	Poland	Forest management	x			
Binder	**Franz**	**Germany**	**Silviculture**	x	x	x	x
Bowditch	**Euan**	**United Kingdom**	**Forest policy**			x	x
Cherubini	Paolo	Switzerland	Forest ecology				x
Chianucci	Francesco	Italy	Forest management				x
Coll	Lluis	Spain	Forest management	x			x
Čurović	Željkca	Montenegro	Landscape architecture				x
Čurović	Milić	Montenegro	Forest ecology				x
Dalponte	Michele	Italy	Remote sensing	x			
delRio	**Miren**	**Spain**	**Forest modeling**				x
Di Lella	Stefania	Italy	Forest ecology	x			
Dimopoulos	Panayotis	Greece	Forest ecology	x			
Dinca	Lucian	Romania	Forest soils	x			
Ditmarová	Ľubica	Slovakia	Forest ecophysiology	x			x
Fayvush	Georgi	Armenia	Forest botany				x
Frizzera	Lorenzo	Italy	Forest ecology	x			
Gianelle	Damiano	Italy	Remote sensing	x			
Heinze	Berthold	Austria	Forest genetics	x			x
Ilieva	iliana	Bulgaria	Forest communication		x		
Kašanin-Grubin	Milica	Serbia	Forest soils				x
Kluvankova	**Tatiana**	**Slovakia**	**Forest economics**			x	x
Kurylyak	Viktor	Ukraine	Silviculture	x			
La Porta	**Nicola**	**Italy**	**Forest pathology**	x	x	x	x
Lavadinovic	Vera	Serbia	Forest economics	x			
Lesinski	**Jerzy**	**Poland**	**Forest biodiversity**		x	x	x
Marshall	John	Sweden	Forest ecophysiology				x
Meszaros	Ilona	Hungary	Forest ecophysiology	x			
Motta	**Renzo**	**Italy**	**Silviculture**	x			x
Neroj	Bozydar	Poland	Forest inventory	x			
Pach	**Maciej**	**Poland**	**Forest management**	x	x	x	x
Panzacchi	**Pietro**	**Italy**	**Forest ecology**	x	x	x	x
Pretzsch	**Hans**	**Germany**	**Forest growth**			x	x
Pšidová	Eva	Slovakia	Forest ecophysiology				x

Puletti	Nicola	Italy	Forest inventory	x			
Radoglou	Kalliopi	Greece	Forest ecophysiology				x
Santopuoli	**Giovanni**	**Italy**	**Forest management**	x	x	x	x
Smith	**Melanie**	**United Kingdom**	**Forest policy**	x	x	x	x
Snorrason	Arnor	Iceland	Forest management	x			
Spathelf	Peter	Germany	Forest growth				x
Stojnic	Srdjan	Serbia	Forest ecophysiology				x
Temperli	**Christian**	**Switzerland**	**Forest inventory**	x	x	x	x
Tognetti	**Roberto**	**Italy**	**Forest ecophysiology**		x	x	x
Tonon	**Giustino**	**Italy**	**Forest ecology**	x	x		x
Torresan	Chiara	Italy	Forest management				
Tsonev	Tsonko	Bulgaria	Forest ecophysiology		x		x
Velikova	**Violeta**	**Bulgaria**	**Forest ecophysiology**	x	x	x	x
Weatherall	**Andrew**	**United Kingdom**	**Forest ecology**	x	x	x	x

Appendix C

Description of network analysis implementation

The analytic network analysis allows to assess pairwise relationships between objects and entities of a network to identify trends and patterns. In this study, the entities are two important tools that deal with forest management, namely the indicators set of sustainable forest management (SFM) developed by Forest Europe in 1998 and recently updated in Madrid 2015 (https://foresteurope.org/sfm-criteria-indicators/), and the forest-related ecosystem services according to the CICES classification version 4, 2012 (**https://cices.eu**). The objects of the network are, on one side the SFM indicators, and on the other side the ecosystem services. The analysis aims to assess and displays the connection between SFM indicators and forest-related ecosystem services according to the preferences of people involved in the project meeting. All the objects where equally considered in this study, and connections were delineated considering the suitability of indicators to provide useful information for assessing adaptation and mitigation forest management.

Analyzing the structure of network is possible to observe some centrality measures which allow to find the most important nodes in a network.

Some of the most commonly centrality parameters are:

- Network size (Ns), which corresponds to the number of nodes forming the network (eqn. 1). In this context, higher values of Ns display high variability in the number of indicators (29) and ecosystem services (23) identified by the participants as useful to assess the climate-smart forestry.

$Ns = \sum \text{nodes}$ (1)

- Network density (Nd), which corresponds to the proportion of existing lines when compared to all the possible lines (eqn. 2). Higher values of Nd reflect the complexity of the network and, in this context, of social values. It reflects the non-trivial topological features as those the relationships between SFM indicators and forest-related ecosystem services.

$$Nd = \frac{\sum(\,ties)}{\text{Rows}*\text{Colums}}\% \quad (2)$$

- The centrality parameters, such as the "Degree", which reflects the number of relationships for each node. Higher values of Degree indicate the central position of the node within the network, reflecting the importance given by people to this node. The Degree is the sum of Indegree and Outdegree values, for ecosystem services and Indicators respectively. The Indegree is the number of ties that each square node receives while the Outdegree is the number of ties that each circle node sends to other nodes. 'Centrality' identifies the node's core importance within the network. This is particularly relevant in this context, because it allows to highlight the key elements that support CLIMO participants in the development of CSF definition.

- Betweenness centrality is based on the number of times a node in the network is "between" other nodes on the causal paths. The Betweenness reflects on how many links depend on this particular node (eqn. 4):

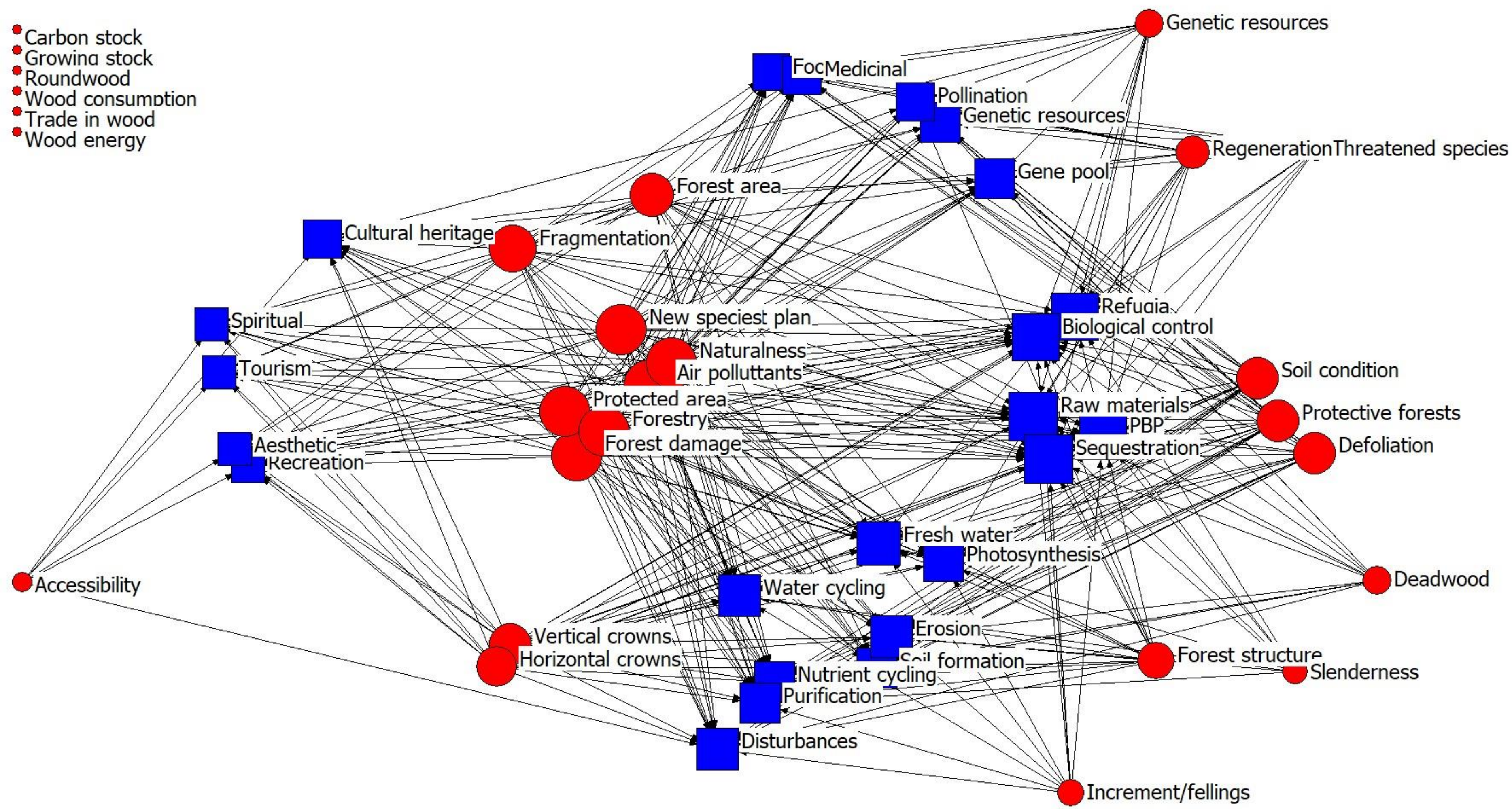
- $$CB(v) = \sum_{s \neq v \neq t \in V} \frac{\partial st(v)}{\partial st}$$

where ∂st is the number of shortest paths from s to t, and ∂st(v) is the number of shortest paths from s to t that pass through a vertex v.

- K-core consists in the identification of particular subsets of the network. A k-core is a maximal group of actors, all of which are connected to some number (k) of other members of the group. If an actor has ties to a sufficient number of members of a group, they may feel tied to that group, even if they do not know many, or even most members. It may be that identity depends on connection, rather than on immersion in a sub-group.

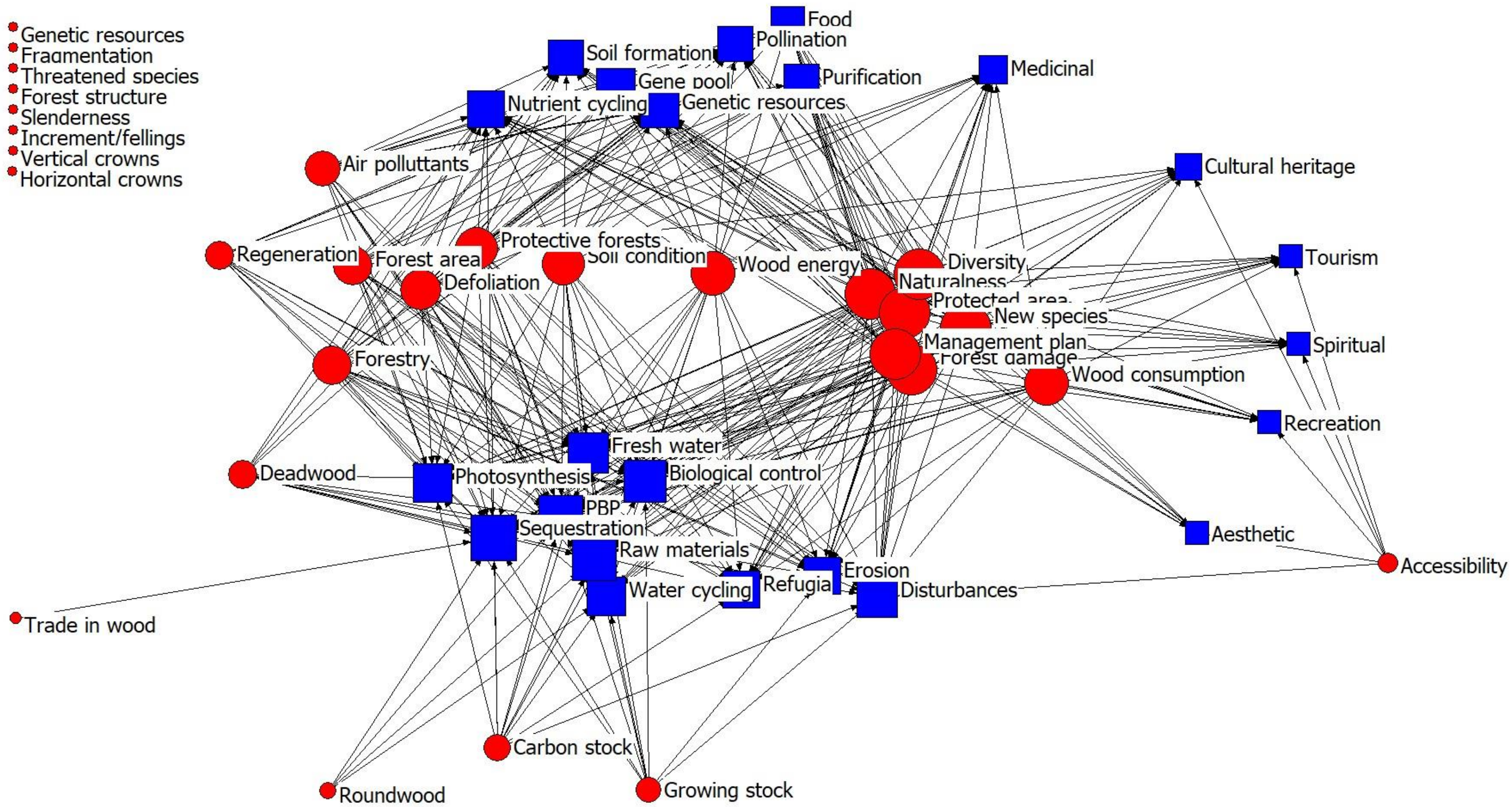
The main output of the analytic network analysis is displayed in the figure S2, S3, and S4.

Figure S2: Suitable Indicators for monitoring the ADAPTATION of Climate-Smart Forestry in mountain ecosystems. Square blue nodes represent the Ecosystem Services, while circle red nodes represent the Indicators for Sustainable Forest Management.



The indicators listed on the top, left corner are not considered by CLIMO participants for the adaptation to climate change.

Figure S3: Suitable Indicators for monitoring the MITIGATION of Climate-Smart Forestry in mountain ecosystems. Square blue nodes represent the Ecosystem Services, while circle red nodes represent the Indicators for Sustainable Forest Management.



The indicators listed on the top, left corner are not considered by CLIMO participants for the mitigation to climate change.

Figure S4: Network analysis of CSF indicators relevance to adaptation and mitigation. The map shows the suitable Indicators for assessing CLIMATE-SMART FORESTRY in mountain ecosystems. This map represents the merged map considering both, adaptive and mitigation targets, according the point of view of CLIMO participants. Square blue nodes represent the Ecosystem Services, while circle red nodes represent the Indicators for Sustainable Forest Management.

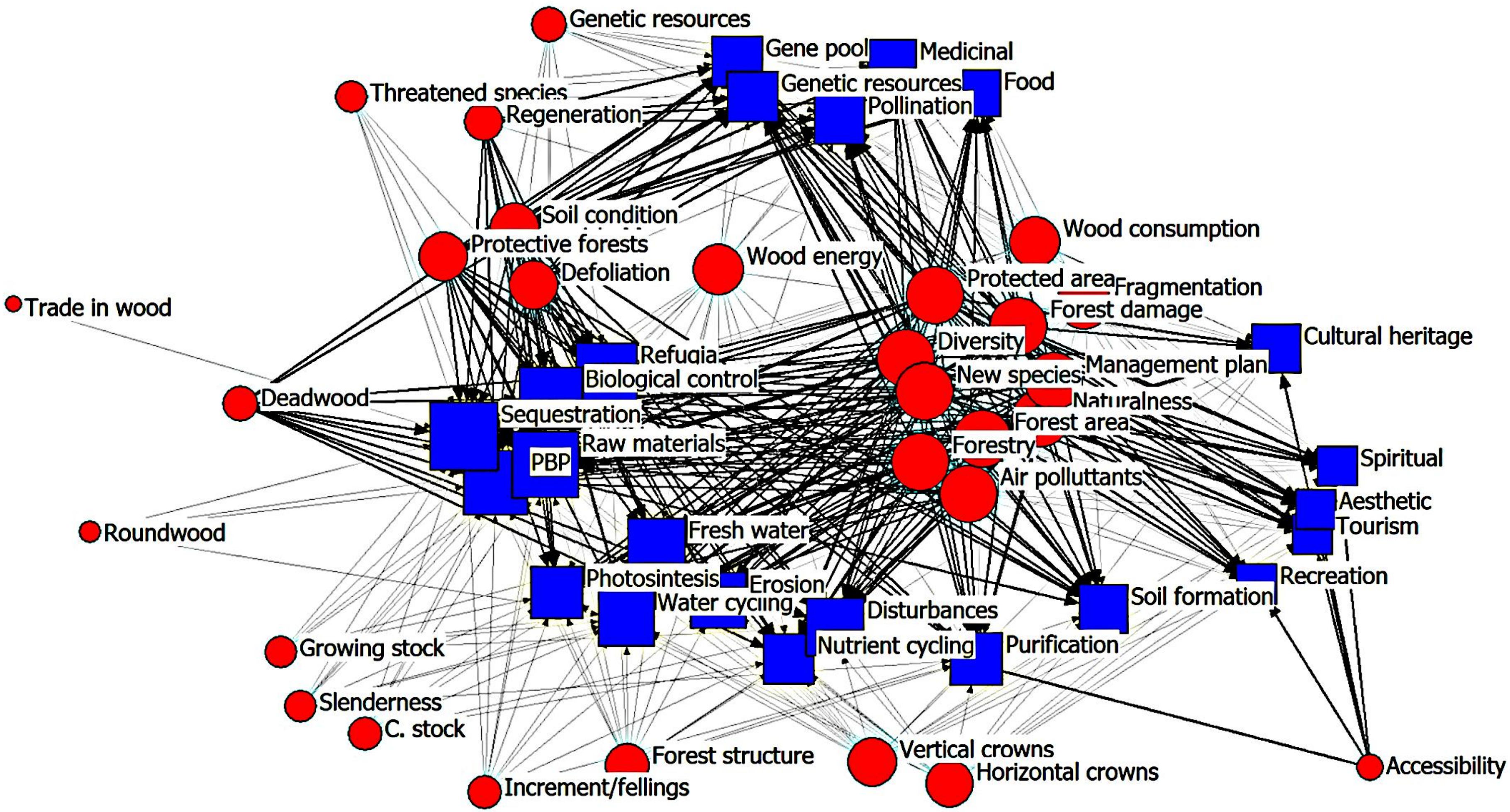


Figure 1

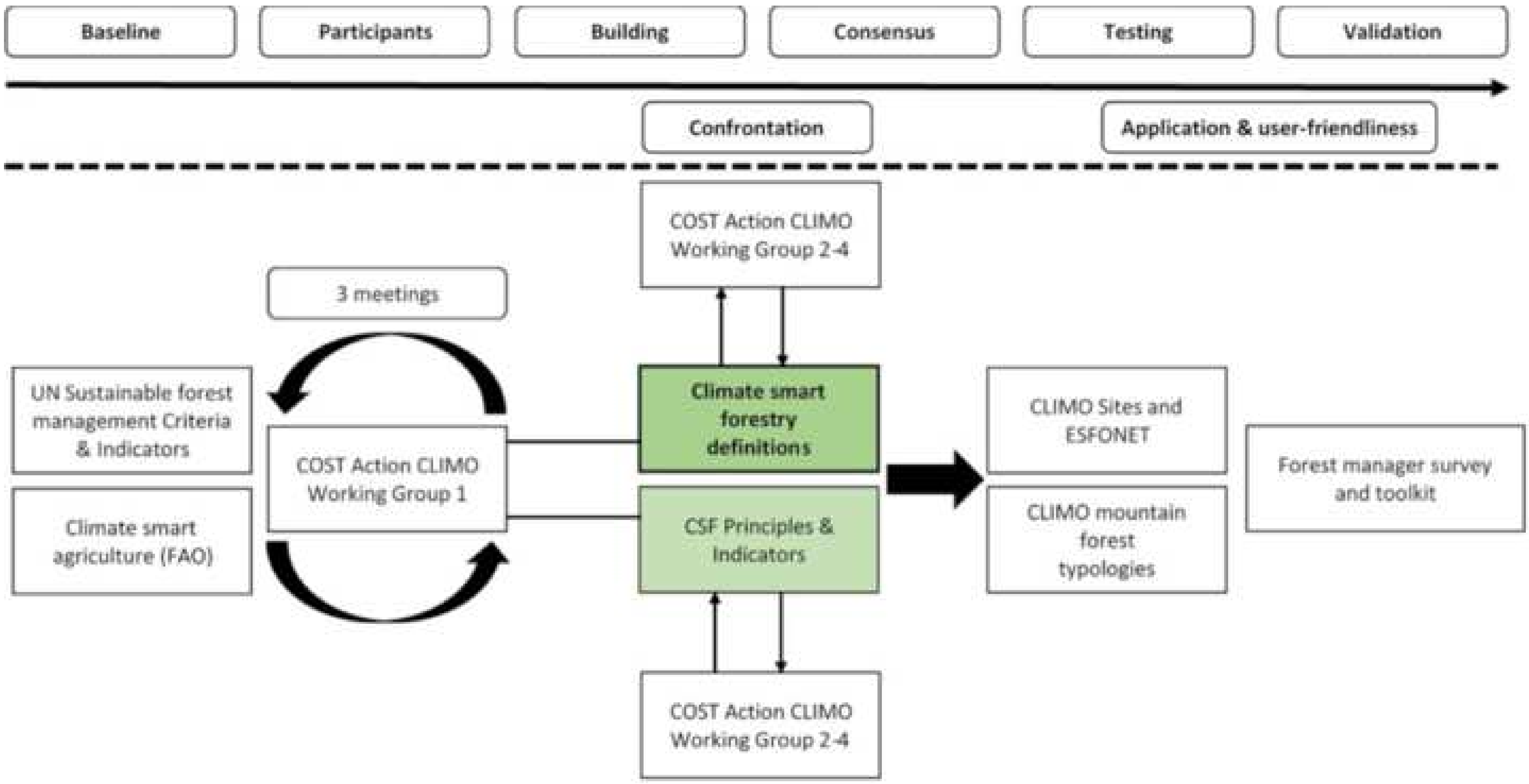

Baseline
Participants
Building
Consensus
Testing
Validation
Confrontation
Application & user-friendliness
COST Action CLIMO Working Group 2-4
3 meetings
UN Sustainable forest management Criteria & Indicators
Climate smart agriculture (FAO)
COST Action CLIMO Working Group 1
Climate smart forestry definitions
CSF Principles & Indicators
CLIMO Sites and ESFONET
CLIMO mountain forest typologies
Forest manager survey and toolkit
COST Action CLIMO Working Group 2-4

Figure 2

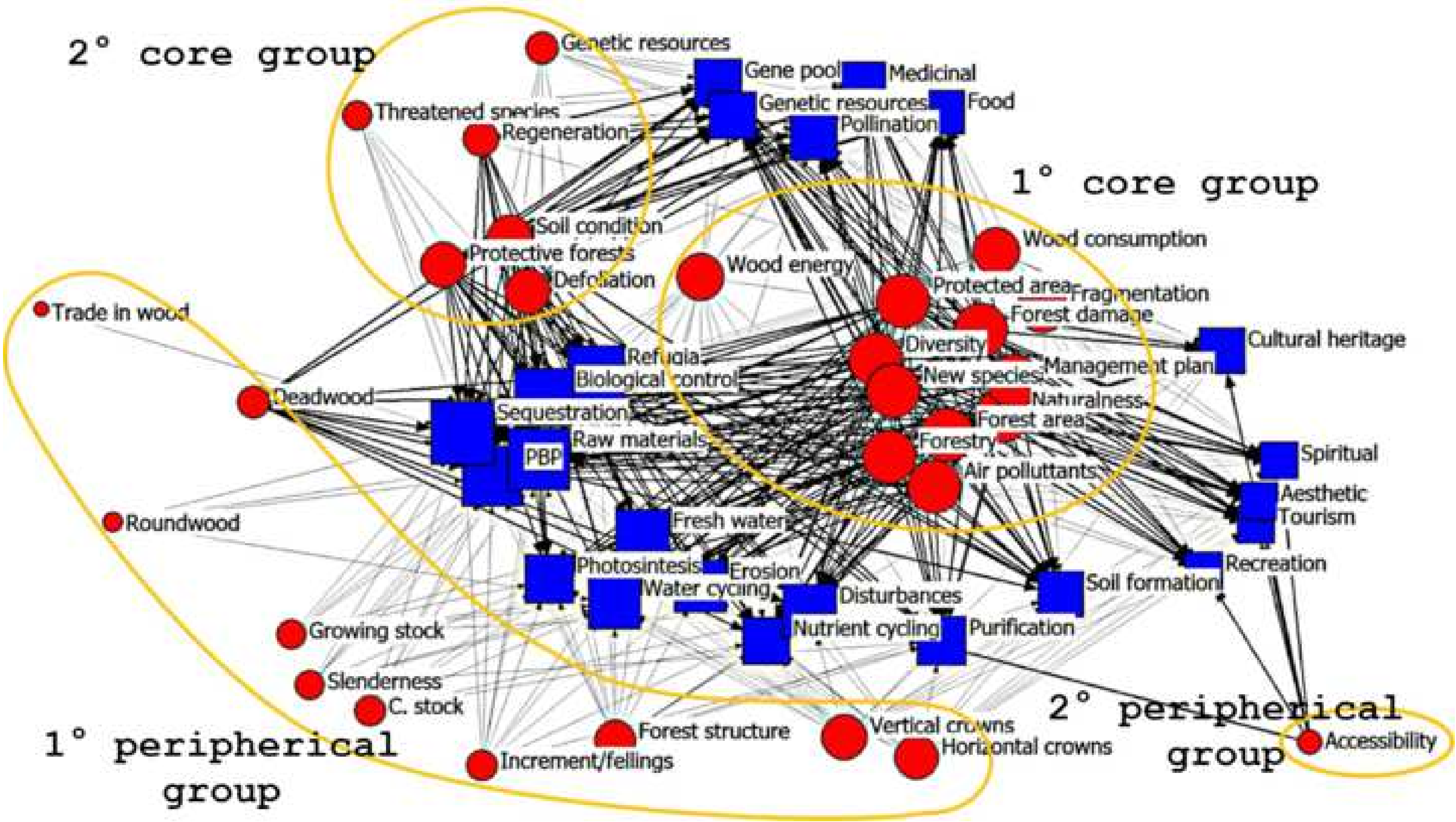
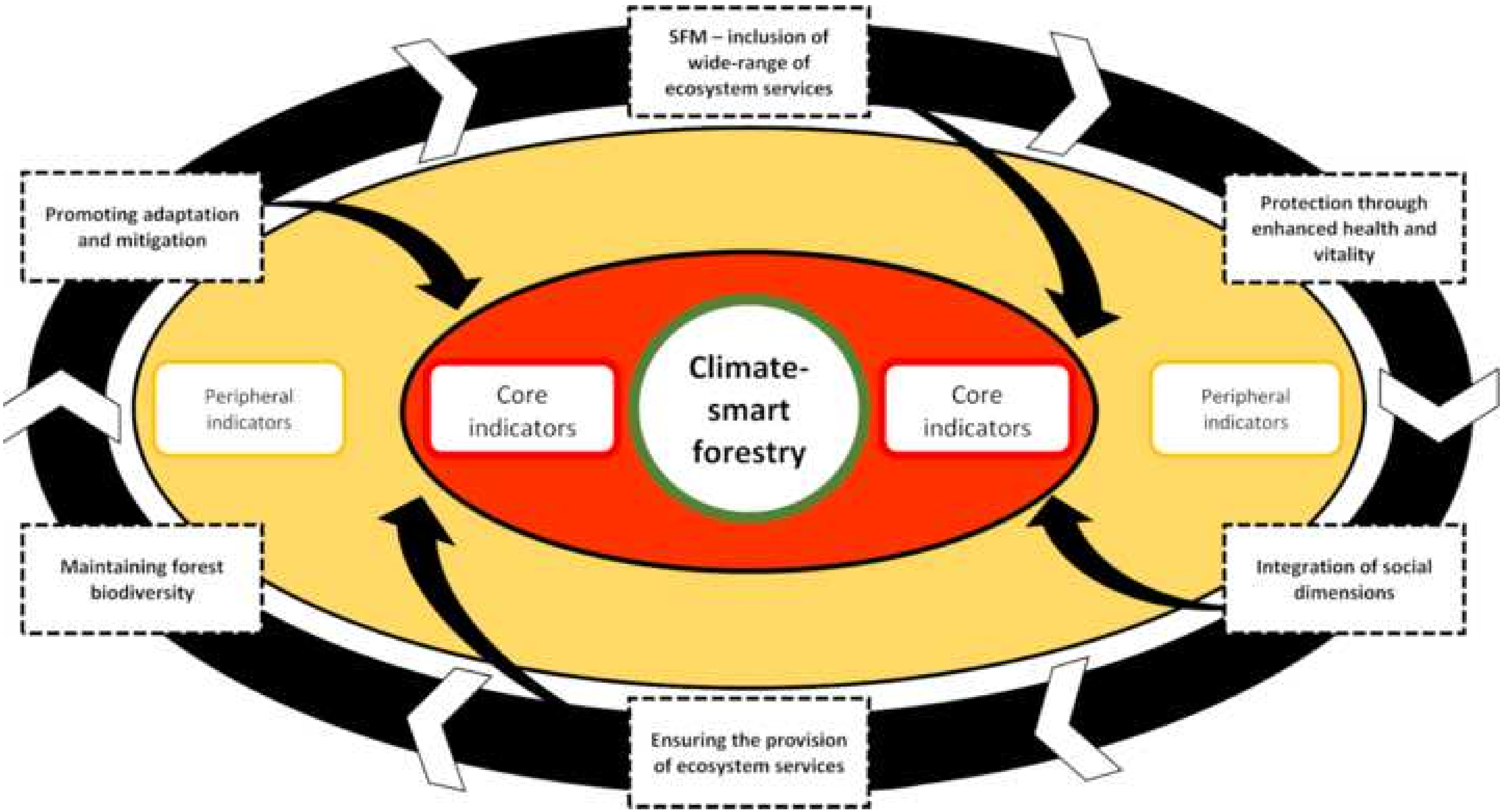

2° core group
Genetic resources
Gene pool
Medicinal
Threatened species
Genetic resources
Food
Regeneration
Pollination
1° core group
Soil condition
Wood consumption
Protective forests
Wood energy
Defoliation
Protected area
Fragmentation
Trade in wood
Forest damage
Diversity
Cultural heritage
Refugia
Management plan
Biological control
New species
Deadwood
Naturalness
Sequestration
Forest area
Raw materials
Forestry
Spiritual
PBP
Air pollutants
Aesthetic
Tourism
Roundwood
Fresh water
Photosintesis
Erosion
Recreation
Water cycling
Soil formation
Disturbances
Growing stock
Nutrient cycling
Purification
Slenderness
C. stock
2° peripherical group
Accessibility
Forest structure
Vertical crowns
1° peripherical group
Increment/fellings
Horizontal crowns

Figure 3


SFM – inclusion of wide-range of ecosystem services
Promoting adaptation and mitigation
Protection through enhanced health and vitality
Peripheral indicators
Core indicators
Climate-smart forestry
Core indicators
Peripheral indicators
Maintaining forest biodiversity
Integration of social dimensions
Ensuring the provision of ecosystem services

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: